Holz als Roh- und Werkstoff 56 (1998) 285–293 © Springer-Verlag 1998

Duration of load behaviour of different sized straight timber beams subjected to bending in variable climate

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This paper is the second in a series which sums up the results of an extensive project to quantify the duration-of-load (DOL) effect on different sized timber beams in different climates. The paper deals with straight (unnotched) beams. The results of various DOL-tests of stepwise and constant bending of LVL and glulam beams are reported and results of modelling outlined. It is concluded that in cyclically varying climate large cross-sections are less affected by the DOL-effect than smaller ones. The results do not show marked difference between LVL and glulam in susceptibility to the DOL-effect.

Zeitstandfestigkeit von Trägern unterschiedlicher Abmessungen. Unverzinkte Träger unter Biegebelastung in wechselndem Klima

Diese Arbeit ist der zweite einer Artikelreihe über ein ausgedehntes Projekt zur Quantifizierung des DOL-Effektes bei Tägern unterschiedlicher Abmessungen unter dem Einfluß verschiedener Umgebungsbedingungen. Hier werden nicht keilverzinkte Träger untersucht. Die Ergebnisse verschiedener DOL-Tests unter stufenweiser und kontinuierlicherBiegebelastung von LVL- und Glulam-Trägern werden vorgestellt. Ebenso werden Modelier-Ergebnisse beschrieben. Es ergab sich, daß große Querschnitte in zyklischem Wechselklima weniger vom DOL-Effekt betroffen sind als kleine Querschnitte. Die Ergebnisse zeigen keinen besonderen Unterschied zwischen Glulam und LVL bezüglich ihrer Empfindlichkeit gegenüber dem DOL-Effekt.

1 Introduction

During 1994–1997 a large research project "Duration-of-load effect on different sized timber beams" was carried out within the AIR programme of the EC. This paper is the second in a set of four papers reporting the results of the project. The overall introduction of the background, objectives, scope and procedures of the entire project is presented in the first paper (Morlier and Ranta-Maunus 1998). The present paper deals with the subproject (Task A) concerned with duration of load effects of straight (unnotched) beams subjected to bending.

The purpose of the experimental programme was to establish a database concerning the DOL effect for timber beams under variable climatic conditions. An important specific issue concerning straight beams is that there is a great deal of uncertainty regarding the correct value of the strength of large members under long-term loading, because DOL-experiments with large sections are rarely performed due to their high cost. The concern is whether the duration of load effect and size effects are independent and additive, or whether they are coupled. The two phenomena have so far been studied separately and they are treated in the codes as additive, which is unfavourable for large timber structures. The particular question is whether the effect of humidity variations, which is known to shorten the lifetime, is linked to beam size.

A review of earlier results of DOL-effect studies is included as part of the introductory paper of this series (Morlier and Ranta-Maunus 1998).

The work with straight beams was carried out at the four laboratories listed in Table 1. Due to the pragmatic nature of the project, the experiments were performed on structural dimensions. Laminated veneer lumber (LVL) and glued laminated wood (glulam) were chosen as test material, since such products are used in sufficient variety of dimensions to warrant a size effect. In addition, such products are more homogeneous than solid wood and allow smaller sample size to produce statistically representative results.

The work included a subtask on bending and tension tests of finger jointed wood. The results of these tests are not included, but have been reported elsewhere (Andreasen and Hoffmeyer 1997).

2 Material

The LVL was of the trademark KERTO-LVL and was delivered by FINNFOREST OY, Finland. The material was selected from normal production made of Finnish spruce wood (*Picea abies*) and was cut to different sizes according to the prescriptions given in the experimental programme.

The spruce logs (*Picea abies*) to be used for the production of the glulam were obtained from the south-east part of Sweden. They were sawn, dried and graded at Kinda sawmill located in the same part of Sweden. The sawing pattern was the so-called 3-exlog which produces three boards one of which contains the pith. Boards including the pith were removed during strength grading. Drying to 12% moisture content was carried out according to the normal practise for the glulam industry in Sweden.

Strength grading was made in two steps, first manually and then by flatwise bending using a grading machine

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The work has been financed by the EC (Project no. AIR2-CT94-1057) and national funding institutes: Technology Development Centre of Finland, The Academy of Finland. The support of these financiers is gratefully acknowledged. Also the appreciation for the financial support of Finnforest Oy is expressed.

Table 1. Laboratories that participated in Task A: straight beams subjected to bending
Tabelle 1. Beteiligte Einrichtungen an Teilprojekt A: unverzinkte Träger unter Biegebelastung

	Name	Logo	Country
Lab 1	Laboratoire de Rhéologie du Bois de Bordeaux,	LRBB	France
Lab 2	VTT Building Technology	VTT	Finland
Lab 3	Department of Structural Engineering and Materials, Technical University of Denmark	DTU	Denmark
Lab 6	Centre Expérimental de Recherches et d'Etudes du Batiment et des Travaux Publics	CEBTP	France

according to the specification "Spruce C35 or better, no pith in board". The grading was verified at the Swedish National Testing Institute (SP) by grading a sub sample using another machine and verifying the calibration by testing 60 boards to failure. The boards to be used for Task A were then transported to Paul Mathis S. A., France, for the manufacture of straight glulam beams.

3 Methods

3.1 Test conditions

The experimental programme for straight beams is laid out in Table 2. The cross-section sizes (width × height) of the tested beams were nominally 45 × 100 mm, 45 × 150 mm, 75 × 100 mm and 75 × 300 mm for LVL and 45 × 100 mm, 45 × 330 mm, 90 × 300 mm and 140 × 445 mm for glulam. Some deviations from the nominal sizes occurred due to manufacture of the specimens from pre-cut dimensions.

Short-term tests were made for all sizes after conditioning at 20 °C and 65%RH and for most sizes also after conditioning at a higher RH (predominantly 85%). Additionally, some short-term test series were made with beams taken from cyclic humidity at the most severe condition when at their highest moisture content. These beams were obviously not at equilibrium moisture content at testing time. The results were used as reference to long-term load tests at similar cyclic humidity.

The long-term test conditions were the same three conditions as chosen for the entire project, viz. constant climate, natural climate and artificial cyclic climate. These conditions are described in detail in (Morlier and Ranta-Maunus 1998). The basic climate condition at which almost all sizes were tested was the artificial cyclic humidity condition. Additionally, some series of LVL beams were tested in natural and constant climates. The natural climate tests were repeated for all seasons: spring, summer, autumn and winter. The natural climate tests were made with both untreated beams and coated beams (vapour barrier paint) to estimate the effect of paint on the DOL-effect.

3.2 Loading

Short-term tests were made according to standard methods (EN 408) with only minor deviations. The long-term tests were made as far as possible with the same loading configuration as the short-term tests. If deviations from the short-term configuration occurred, necessary corrections were applied to the long-term load levels.

The basic loading pattern of the long-term tests was stepwise loading, but constant load tests were also carried out. The duration of the long-term tests were targeted to a few months each. The stress levels therefore were targeted to obtain a median time to failure in about two months; this means that 50% of the specimens should fail during that time. For stepwise loading the additional requirement was imposed that no failures should occur at the lowest load level, although this was not always achieved. In the cyclic humidity tests, the loading increments were synchronised with the humidity cycles so that load increments were made at descending moisture content.

3.3 Long-term test arrangements

Special test frames for the execution of the long-term tests were built at each laboratory. For the execution of tests in natural climate for cross-section sizes 45 × 100 mm and 45 × 150 mm of LVL, Lab 1 (LRBB) erected 20 double frames in a shed experiencing covered outdoor climate. Beams were mounted vertically in the frames, and load was applied by pneumatic jacks (Fig. 1).

Ten load frames were build into a large climatic chamber for testing of the larger LVL-beams (75 × 100 and

Table 2. Experimental programme of Task A: straight beams subjected to bending
Tabelle 2. Versuchsprogramm des Teilprojekts A: unverzinkte Träger unter Biegebelastung

Material	Nominal size b × h × l, mm	Short term	Long-term		
			Cyclic	Natural	Constant
LVL	45 × 100 × 2000	Lab 1	Lab 3	Lab 1	Lab 1
	45 × 150 × 2000	Lab 1		Lab 1	Lab 1
	75 × 100 × 4300	Lab 2	Lab 2		
	75 × 300 × 4300	Lab 2	Lab 2		Lab 2
Glulam	45 × 100 × 2000	Lab 3	Lab 3		
	45 × 330 × 5000	Lab 6	Lab 6		
	90 × 300 × 5000	Lab 6	Lab 6		
	140 × 445 × 5000	Lab 6	Lab 6		
Finger	45 × 100 × 2000	Lab 3	Lab 3		
joints[1]	33 × 140 × 300	Lab 3	Lab 3		

[1] Results of tests with finger jointed wood are not included in this paper.

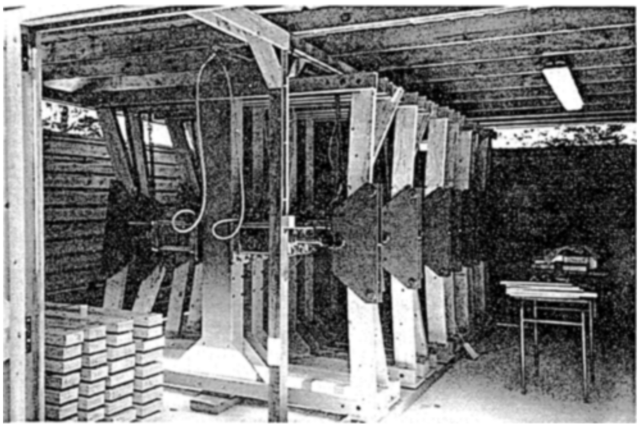

Fig. 1. Loading frames at Lab 1, LRBB, for tests of small LVL beams at sheltered outdoor climate
Bild 1. Lastaufbringung in Labor 1 (LRBB) zur Prüfung kleiner LVL-Träger in geschütztem Außenklima

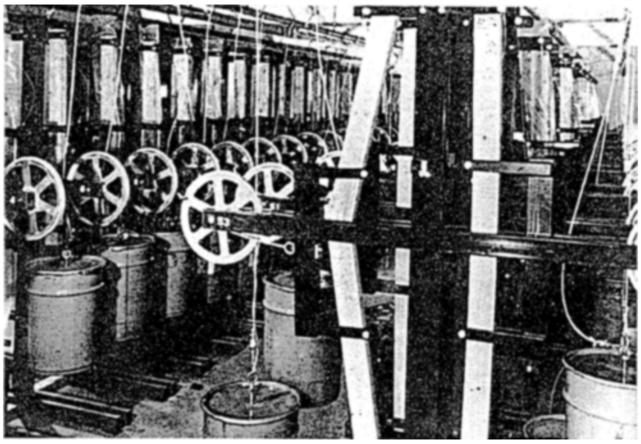

Fig. 3. Loading frames at Lab 3, DTU, for tests of small LVL beams and glulam beams at controlled climate
Bild 3. Lastaufbringung in Labor 3 (DTU) zur Prüfung kleiner LVL- und Glulam-Träger in kontrolliertem Klima

75 × 300) at Lab 2 (VTT). Loading was applied by a set of disk springs (Fig. 2). The load was raised by tightening the springs. In order to compensate the force relaxation due to creep of the specimens the spring forces were regularly checked and re-tightened to keep up the correct load magnitude. The climate chamber was set at 20 °C and either at constant 85%RH or to follow the artificial cyclic humidity between 90 and 55%RH. In the constant condition tests, the constant MC of the beams was further secured by sealing the specimens by an impervious paint. At the cyclic condition the beams were of course without any treatment.

At Lab 3 (DTU) 45 loading frames for beam size 45 × 95 were erected into a climatic chamber for long-term tests of LVL and glulam. The beams stood vertically in the frames (Fig. 3) and the load was applied by weights and pulleys. The conditions were: temperature 20 °C and either constant RH 65%, constant RH 85% or the cyclic RH between 55 and 90%. The constant conditions were applied as follows: beams were conditioned at either 65% or 85%RH and then encased in polyethylene tubes and taken for tests in a climatic chamber at 55%RH. To keep the 85%RH, a saturated KNO_3 salt solution was injected regularly into the plastic tubes. To keep the 65% condition no addition of moisture was necessary. Constant MC was verified by measurements in both cases.

At Lab 6 (CEBTP) tests frames were built for the larger glulam beams (40 × 330 mm, 83 × 330 mm, 125 × 495 mm). The beams were mounted horizontally and the load was applied by dead loads for the first step and a hydraulic jack for the following steps. The hydraulic load was maintained by a steel beam having a spring effect. Condition was the cyclic RH between 55 and 90%.

More details of the experimental work can be found in the original reports of the participating labs: Lebatteux and Galimard (1996), Fonselius and Ranta-Maunus (1996), Ranta-Maunus et al. (1998), Andreasen and Hoffmeyer (1997).

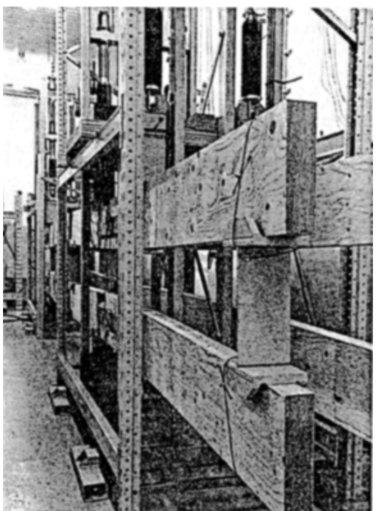

Fig. 2. Loading frames at Lab 2, VTT, for tests of large LVL beams at controlled climate
Bild 2. Lastaufbringung in Labor 2 (VTT) zur Prüfung großer Träger in kontrolliertem Klima

4 Results

4.1 Short-term results

The obtained short-term results include the strength of the specimens and in most cases also the modulus of elasticity (MOE). Both strength and MOE were calculated by classical linear beam theory formulas. In addition to mean strength values the 50th and 5th percentiles of the Weibull and Log-normal distribution of all the series have been determined. The short-term strength results are presented in condensed form in Tables 3 and 4; MOE results are found in the original reports mentioned above.

The primary purpose of the short-term tests was to serve as reference for the long-term tests. The results may also be used to assess the effect of size on strength (Fonselius and Ranta-Maunus 1996). Since tests were made at more than one moisture condition, the results provide means to assess the influence of moisture content on strength. This has been made as a part of the work in order to obtain the reference short-term strengths for those long-term test series, in which the median failure occurred at a moisture content other than the short-term tests. The work was made separately for different sizes so as to not mix size effect into the analysis. In Fig. 4 the short-term strength as function of moisture content has been given for the sizes

Table 3. A summary of short-term results on straight LVL beams subjected to bending (L = span)
Tabelle 3. Zusammenfassung der Kurzzeit-Ergebnisse an unverzinkten LVL-Trägern unter Biegebelastung

	Size b × h × l mm	Sample size	Climate %RH	MC %	Mean MPa	COV %	Weibull		Log-normal	
							$f_{W50\%}$ MPa	$f_{W5\%}$ MPa	$f_{L50\%}$ MPa	$f_{L5\%}$ MPa
1	45 × 100 × 2000	30		9.0	60.0	7	60.6	52.0	59.9	53.0
2	45 × 150 × 2000	30		9.0	59.5	8	60.0	49.7	59.3	52.0
3	45 × 100 × 2000	30		14.5	49.0	6	49.4	44.2	48.9	44.6
4	45 × 150 × 2000	30		14.5	50.1	6	50.4	43.1	50.0	45.0
5	45 × 95 × 1720	15	65	10.6	57.6	8.9	55.9	51.7	57.4	50.0
6	45 × 95 × 1720	15	85	16.5	47.0	8.0	45.8	41.4	46.9	41.4
7	45 × 95 × 1720	15	55–90[1]	15.5	47.6	7.0	46.5	43.4	47.5	42.5
8	75 × 100 × 2000	20	65	10.6	53.7	6.7	54.2	46.9	53.6	48.0
9	75 × 100 × 2000	20	~75[2]	12.0	51.2	8.0	51.7	43.6	51.0	44.7
10	75 × 100 × 1800	20	65	10.5	57.5	7.5	58.0	49.7	57.3	50.7
11	75 × 300 × 3900	20	65	10.5	50.1	8.2	50.6	42.7	49.9	43.7
12	75 × 300 × 3900	10	→90[3]	15.4	47.1	7.2	47.5	40.7	47.0	41.8
13	75 × 300 × 3900	10	85	14.1	45.7	3.9	45.9	42.8	45.7	42.9

[1] Beams were taken out of the cyclic condition during high humidity for short-term testing (they were not at equilibrium).
[2] Climatic chamber was set to 85%, but due to malfunction the true humidity was lower.
[3] Beams were not at equilibrium.

Table 4. A summary of short-term results on straight glulam beams subjected to bending (L = span)
Tabelle 4. Zusammenfassung der Kurzzeit-Ergebnisse an unverzinkten Glulam-Trägern (Brettschichtholz) unter Biegebelastung

	Size b × h × l mm	Sample size	Climate %RH	MC %	Mean strength MPa	COV %	Weibull		Log-normal	
							$f_{W50\%}$ MPa	$f_{W5\%}$ MPa	$f_{L50\%}$ MPa	$fL_{5\%}$ MPa
1	45 × 95 × 1720	14	65	12.2	53.0	21.0	54.1	35.7	51.6	34.5
2	45 × 95 × 1720	14	55–90[1]	16.6	48.3	18.1	45.3	35.6	47.5	35.2
3	45 × 95 × 1720	14	65	12.9	50.1	12.6	47.9	39.0	49.7	40.3
4	45 × 95 × 1720	14	55–90[1]	18.0	49.9	10.0	48.1	38.9	49.6	41.9
5	83 × 330 × 5000	10	65	12.1	49.8	19.5	50.3	31.8	48.9	35.5
6	40 × 330 × 5000	10	65	10.9	47.0	11.9	47.7	38.0	46.7	38.1
7	125 × 495 × 5000	8	65	10.6	41.6	14.1	42.3	31.5	41.3	32.7
8	125 × 495 × 7000	6	65	13.6	43.5	11.9	44.1	35.1	43.2	35.4
9	83 × 330 × 5000	10	55–90[1]	17.2	48.8	14.0	49.5	37.2	48.4	37.9
10	40 × 330 × 5000	10	55–90[1]	16.8	45.6	11.9	46.1	35.3	45.3	37.2
11	125 × 495 × 5000	10	55–90[1]	17.5	42.0	11.8	42.8	35.7	41.7	33.7

[1] Beams were taken out of the cyclic condition during high humidity for short-term testing (they were not at equilibrium).

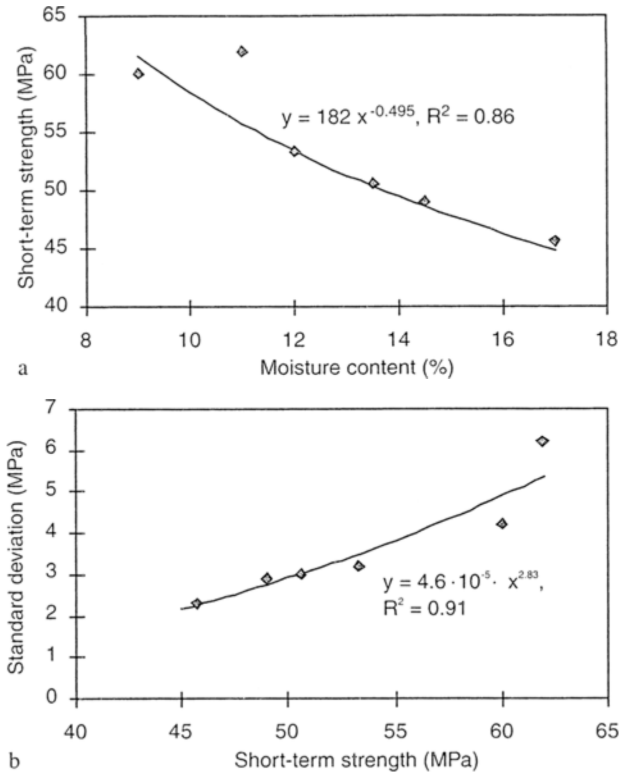

Fig. 4a and b. Short-term strength as a function of moisture content for beam sizes 45 × 100 mm and 45 × 150 mm of LVL; (a) Mean strength vs. moisture content. (b) Standard deviation of strength vs. mean strength. The two sizes have been treated together because a statistical analysis showed the size effect between these series to be negligible

Bild 4a und b. Kurzzeitfestigkeit in Abhängigkeit von der Feuchte für LVL-Träger mit den Abmessungen 45 × 100 und 45 × 150 mm; (a) Mittlere Festigkeit; (b) Standardabweichung der Festigkeit. Träger beider Abmessungen wurden gemeinsam geprüft, weil die statistische Prüfung ergab, daß der Größeneinfluß vernachlässigbar ist

45 × 100 mm and 45 × 150 mm of LVL; these sizes have been combined since a statistical analysis showed that the size effect was negligible between these series.

4.2 Long-term results

The long-term results include basically the stress-level at failure and time-to-failure of each specimen. In many cases the long-term deformations (creep deflections) were also recorded. Due to the vast amount of results obtained during the whole project, each test series cannot be considered separately in this paper. Instead, a condensed summary of all test series is presented in Tables 5 and 6. The features of the strength results of single test series are described by examples in the following. The creep measurements are found in the original reports.

As an illustration of the outcome of the long-term tests, the results of three series, with cross-section size 45 × 100 mm or 45 × 95 mm have been selected into Fig. 5. The beams in these series have been subjected to stepwise loading, but each series has experienced a different climatic condition, either constant, natural or artificial cyclic. The stress levels of the series were not the same and the times-to-failure are therefore not directly comparable.

In order to make the different results comparable, time-to-failure plots were drawn as shown in Fig. 6 and an analysis performed as described in the following. DOL trend lines were drawn first in two different ways: (1) using the ranking method for determining the stress levels of individual specimens and subsequently drawing the trend line as a line fit to obtained points and (2) using the mean short-term strength to determine the stress levels for all specimens and then drawing the trend line from the point representing short-term strength through the point representing the stress level and time to failure of the median of the long-term tested sample, Fig. 6. The second method proved to be more useful and was adopted as the general one in the project, since it allows the determination of the trend line also in variable climates, in which specimens may fail at different moisture contents. In this approach the short-term reference strength of the median failure can always be estimated based on the average moisture content at failure time, or, if short-term tests were made for specimens taken out of cyclic condition, based on the actually measured value. The median failure was defined as the time when the median failure occurs in case of odd number of specimens or as the average of the two median failures in case of even number of specimens (e.g. the 8th failure in the case of a sample size of 15 or the average of the 8th and 9th failure in the case of a sample size of 16). For stepwise loading the time-to-failure was determined as the difference of the time of the median failure and the last load increment before it. By using the obtained DOL-trend lines the results of each series were extrapolated to a reference load duration of six months (Fig. 6). The corresponding strength levels were used to define a k_{DOL} factor which describes the susceptibility to the DOL-effect measured in the different test series. The lower the obtained k_{DOL} value, the more prone is the material to the DOL effect. In addition, a factor k_{MC} was defined to quantify the effect of moisture content on long-term strength as compared to tests at standard conditions (65%RH, 20 °C). The product of the two factors was denoted k_{mod}. These factors have been discussed in detail by Morlier and Ranta-Maunus (1998). This methodology provides practical means to estimate the differences of DOL-behaviour in different conditions.

The results of all the long-term tests with straight beams have been summarised in Tables 5 and 6 by using the two factors k_{DOL} and k_{mod}, see also Fig. 8. Further explication of the experimental long-term results will be given below as part of the discussion.

5 Modelling

During the project new approaches to the modelling and mathematical treatment of the DOL-effect were developed.

Damage accumulation models can provide predictions for very long-term loading. However, it has been demonstrated (Lebatteux 1997) that strength factors defined using such models are highly dependent on the method used to present the results and to fit a damage accumulation model. So, the long-term prediction (DOL strength factor) has to be carefully studied. Galimard et al. (1997) developed a theoretical approach to optimise the cost of DOL-experiments, i.e. the number of beams that should be tested to provide a required accuracy at a given stress level for extrapolated DOL-factors. The variability analysis is based on a simple damage accumulation model. However, the validity of the model is not discussed. In the study, no variation of the time to failure is assumed, although the experimental results have shown its instability for a high

Table 5. A summary of long-term results on straight LVL beams subjected to bending (L = span)
Tabelle 5. Zusammenfassung der Langzeit-Ergebnisse an unverzinkten LVL-Trägern unter Biegebelastung

	Size b × h × l mm	Climate[1] or %RH	Coating[2]	Loading	Strength factors at 6 months	
					k_{DOL}	k_{mod}
1	45 × 100 × 2000	Spring 95	nc	stepwise	0.87	0.83
2	45 × 100 × 2000	Spring 95	c	stepwise	0.70	0.66
3	45 × 100 × 2000	Summer 95	nc	stepwise	0.78	0.81
4	45 × 100 × 2000	Summer 95	c	stepwise	0.72	0.75
5	45 × 100 × 2000	Autumn 95	nc	stepwise	0.79	0.73
6	45 × 100 × 2000	Autumn 95	c	stepwise	0.87	0.87
7	45 × 100 × 2000	Winter 95/96	nc	stepwise	0.94	0.81
8	45 × 100 × 2000	Winter 95/96	c	stepwise	0.80	0.68
9	45 × 100 × 2000	Summer 96	nc	constant	0.78	0.79
10	45 × 100 × 2000	Summer 96	c	constant	0.72	0.76
11	45 × 100 × 2000	Summer 96	nc	constant	0.88	0.91
12	45 × 100 × 2000	Summer 96	c	constant	0.82	0.86
13	45 × 100 × 2000	Autumn 96	nc	constant	0.89	0.81
14	45 × 100 × 2000	Autumn 96	c	constant	0.81	0.80
15	45 × 100 × 2000	Autumn 96	nc	constant	0.89	0.86
16	45 × 100 × 2000	Autumn 96	c	constant	0.93	0.92
17	45 × 100 × 2000	Winter 96/97	nc	constant	0.86	0.73
18	45 × 100 × 2000	Winter 96/97	c	constant	0.81	0.69
19	45 × 100 × 2000	Spring 97	nc	constant	0.90	0.83
20	45 × 100 × 2000	Spring 97	nc	constant	0.92	0.89
21	45 × 100 × 2000	Spring 97	c	constant	0.85	0.83
22	45 × 150 × 2000	Spring 95	nc	constant	0.75	0.72
23	45 × 150 × 2000	Spring 95	c	constant	0.75	0.71
24	45 × 150 × 2000	Summer 95	nc	constant	0.81	0.85
25	45 × 150 × 2000	Summer 95	c	constant	0.72	0.75
26	45 × 150 × 2000	Autumn 95	nc	constant	0.78	0.72
27	45 × 150 × 2000	Autumn 95	c	constant	0.80	0.80
28	45 × 150 × 2000	Winter 95/96	nc	constant	0.78	0.68
29	45 × 150 × 2000	Winter 95/96	c	constant	0.79	0.67
30	45 × 95 × 1720	65	nc[3]	stepwise	0.74	0.74
31	45 × 95 × 1720	65	nc[3]	constant	0.70	0.70
32	45 × 95 × 1720	85	nc[4]	stepwise	0.67	0.55
33	45 × 95 × 1720	85	nc[4]	constant	0.66	0.54
34	45 × 95 × 1720	Cyclic 55–90	nc	stepwise	0.67	0.56
35	45 × 95 × 1720	Cyclic 55–90	nc	constant	0.64	0.53
36	75 × 100 × 2000	Cyclic 55–90	nc	stepwise	0.67	0.60
37	75 × 300 × 3900	Cyclic 55–90	nc	stepwise	0.75	0.69
38	75 × 300 × 3900	85	nc/c[5]	stepwise	0.68	0.63

[1] The seasons refer to sheltered outdoor condition in Bordeaux. Cyclic 55–90 refers to the artificial cyclic humidity condition with period of 28 d.
[2] nc – non-coated
c – coated with an impervious paint
[3] Beams were conditioned at 65%RH and then sealed in polyethylene tubing and then kept at 55%RH during testing. Constant MC was verified by measurements.
[4] Beams were conditioned at 85%RH and then sealed in polyethylene tubing into which saturated KNO_3 solution was injected regularly. Constant MC was verified by measurements.
[5] Combined result of two series which were both made at 85%RH. In one of the series specimens were without coating, in the other beams were sealed by an impervious paint.

stress level. The sensitivity analysis has been restricted to the uncertainty on the actual stress level, which is not very significant for a homogenised wood product like LVL (low variability of strength). Surprisingly, however, the calculated uncertainty on DOL factors is low (<5%), even for long-term prediction.

Hanhijärvi (1997) developed a calculation method for estimating the long-term strength behaviour of wooden beams of different cross-sections in variable climates. The method is based on FE-analysis, which calculates the moisture fluctuations and the creep phenomena occurring inside the cross-section. The creep model used is non-linear with respect to stress and takes into account the non-symmetrical behaviour of the tension and compression sides. The creep analysis is supplemented by failure analysis as explained in the following. A local damage variable is defined at each point of the cross-section. The local damage variable is based on the evolution of strain energy density as function of local stress and strain and is defined as the ratio of the strain energy density and its critical value. The critical value in turn is a function of moisture content and stress mode (tension or compression). In this way a distribution of the local damage variable is defined across the whole cross section, or in fact, the distributions of two variables, one describing the tension side and the other describing the compression side. Based on the distribution of the local damage variables, two global damage parameters representing the tension and compression states of the cross-section are defined using spatial integration in a similar fashion as in

Table 6. A summary of long-term results on straight glulam beams subjected to bending (L = span)
Tabelle 6. Zusammenfassung der Langzeitergebnisse an nicht verzinktem Brettschichtholz unter Biegebelastung

	Size b × h × l mm	Climate[1] or %RH	Coating	Loading	Strength factors at 6 months	
					k_{DOL}	k_{mod}
1	45 × 95 × 1720	65	nc[2]	stepwise	0.72	0.72
2	45 × 95 × 1720	Cyclic 55–90	nc	stepwise	0.57	0.54
3	40 × 330 × 5000	Cyclic 55–90	nc	stepwise	0.75[3]	0.75[3]
4	83 × 330 × 5000	Cyclic 55–90	nc	stepwise	0.74[3]	0.74[3]
5	125 × 495 × 5000	Cyclic 55–90	nc	stepwise	0.74[3]	0.74[3]

[1] Cyclic 55–90 refers to the artificial cyclic humidity condition with period of 28 d.
[2] Beams were conditioned at 65%RH and then sealed in polyethylene tubing and then kept at 55%RH during testing. Constant MC was verified by measurements.
[3] For the large glulam beams reference strength at ~65%RH was used, because short-term tests for beams taken from the cyclic conditions did not show much deviation from the constant condition at 65%RH. Therefore $k_{mod} = k_{DOL}$ has been taken. However, the beams may not have conformed thoroughly to the cyclic moisture before short-term testing due to too few cycles at cyclic humidity. If so, the k_{DOL} values should be corrected slightly upwards

the Weibull theory of weakest link. The final failure criterion of the whole beam is that, whenever either one of the global damage parameters reaches one, the beam fails. The spatial integration allows to take into account the distribution of the local damage variable and to incorporate size effect into the analysis. The model suits better for modelling time-to-failure of reconstituted wood, especially LVL, than solid wood, as the model assumes homogenous material, but it can be used for wood also. The model was applied to experimental results of the project with good accuracy as illustrated in Fig. 7.

Nielsen (1997) extended his damaged viscoelastic material (DVM) theory to take into account not only the static fatigue (i.e. the DOL-effect) but also the case of pulsating load. The new model accounts for the viscoelastic nature of wood and thus predicts wood under high frequency load to behave as a "Wöhler material" and wood under slow frequency load cycles to behave almost as a "Palmgren-Miner material".

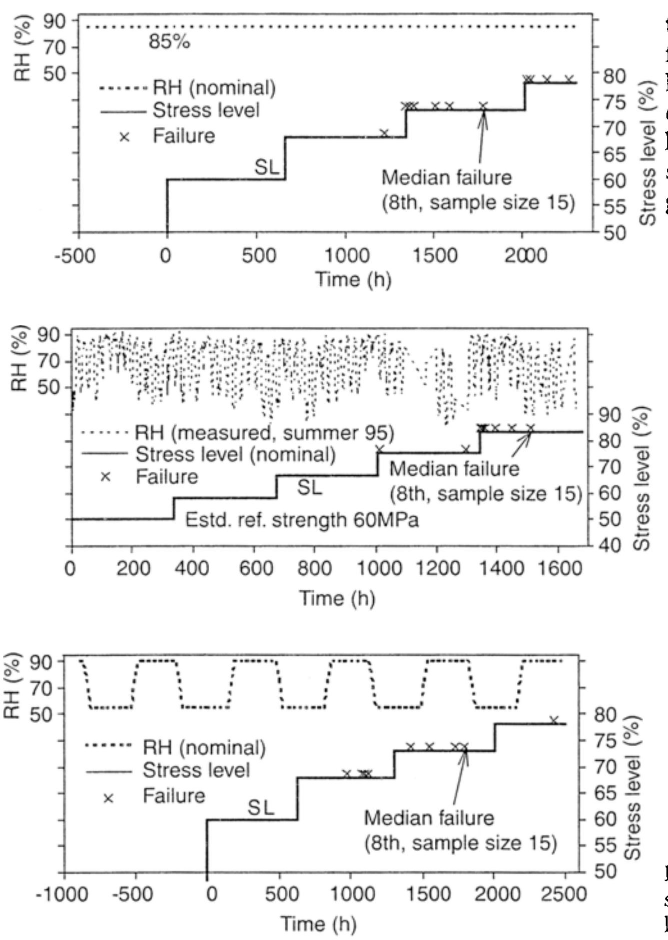

Fig. 5a–c. Examples of long-term test results. Results of non-coated LVL-beams of size 45 × 100 mm (45 × 95 mm) at (a) constant humidity, (b) natural humidity in summer, and (c) artificial cyclic humidity
Bild 5a–c. Beispiele für die Ergebnisse der Langzeitfestigkeit. Ergebnisse an LVL-Trägern der Abmessungen 45 × 100 mm (bzw. 45 × 98 mm): (a) bei konstanter Feuchte; (b) bei natürlicher Feuchte im Frühjahr; (c) bei künstlichem Wechselklima

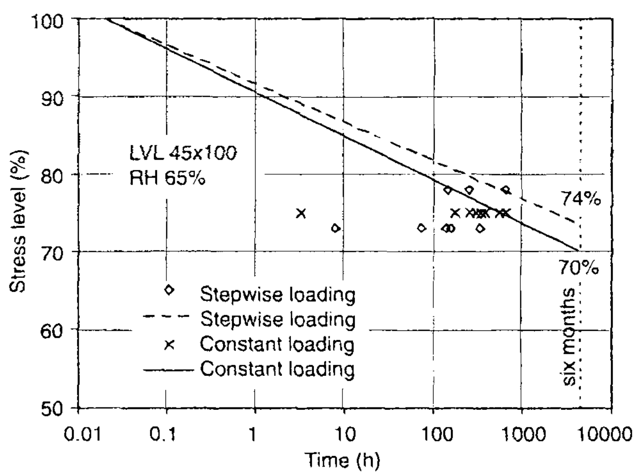

Fig. 6. Determination of the DOL-trend line for long-term test series. Note that the time to failure is calculated from the previous load increment in case of stepwise loading. The median failure (in this case 8th failure of 15 specimens) is used to draw the trend line, which is used to determine the k_{DOL} factor at 6 months load duration
Bild 6. Bestimmung der Trendlinie des DOL-Effektes für Langzeitserien. Zu beachten ist, daß der Bruchzeitpunkt berechnet ist aus der vorangegangenen Lasterhöhung (im Falle stufenweiser Belastung). Der mittlere Bruch (hier die 8. von 15 Proben) wird für die Trendlinie verwendet, woraus der Reduktionsfaktor (k_{DOL}) bei 6 monatiger Belastung bestimmt wird

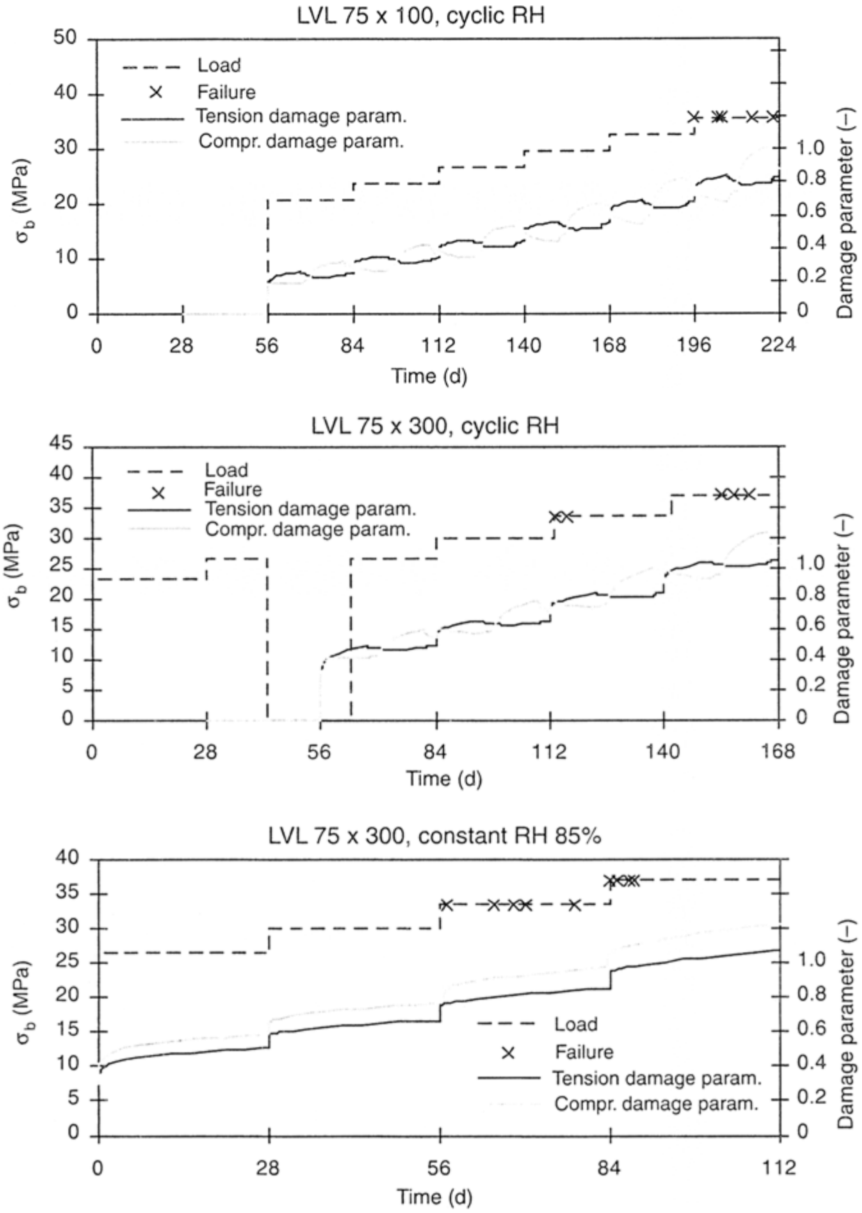

Fig. 7a–c. Prediction of long-term strength of LVL beams with comparison to test results. (a) beam size 75 × 100 mm, cyclic humidity; (b) beam size 75 × 300 mm, cyclic humidity; (c) beam size 75 × 300 mm, constant humidity. 'Load' denotes the nominal edge stress (σ_b) during test. The median beam is predicted to fail when either damage parameter value reaches 1

Bild 7a–c. Vorhersage der Langzeitfestigkeit von LVL-Trägern im Vergleich mit den Prüfergebnissen: (a) Abmessung 75 × 100 mm, Wechselklima; (b) Abmessung 75 × 300 mm, Wechselklima; (c) Abmessung 75 × 300 mm, konstante Feuchte. "Load" bedeutet die nominelle Randspannung (σ_b) während der Prüfung. Der mittlere Träger sollte zu Bruch gehen wenn einer der Schädigungsparameter den Wert 1 erreicht

6 Discussion

The most important observation is that the effect of load duration at varying humidity conditions is a function of cross sectional size: larger cross sectional sizes are less affected than smaller sizes. This is seen for LVL in Table 5 by comparing k_{DOL} values of items 34–37. For glulam this is even more evident when comparing the k_{DOL} values of items 2–5 in Table 6. This is a particular important observation, since the majority of earlier DOL-experiments were carried out using small specimen sizes.

Another important observation is that the stepwise loading procedure produces similar k_{mod} values as the constant loading procedure (Table 5). This is a significant result, since it increases the reliability of the results compared to real service structures.

Further, the lowest k_{mod} values are obtained in the tests at the artificial cyclic humidity. The cyclic humidity between 55 and 90%RH with one month period thus proves to be more severe to the beams than does the natural climate.

The results do not show any marked difference in susceptibility to DOL between LVL and glulam, when similar

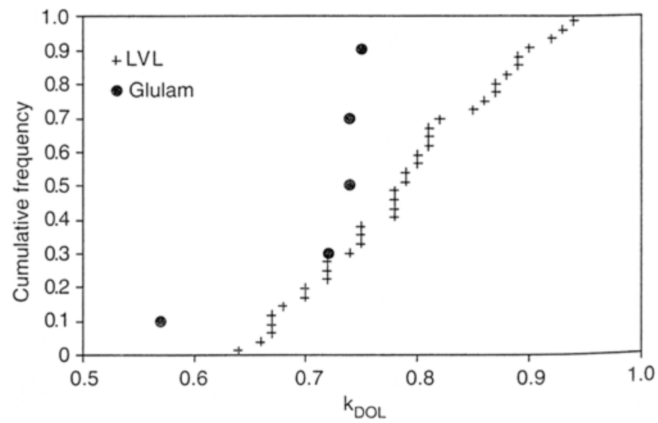

Fig. 8. Cumulative frequency plot of observed k_{DOL} factors at load duration of six months for LVL and Glulam beams. Note that the plot does not allow a direct comparison between the two materials because of different test conditions and sizes

Bild 8. Kumulative Häufigkeit der beobachteten Reduktionsfaktoren k_{DOL} bei einer Belastungsdauer von 6 Monaten für LVL- und Glulam-Träger. Der Graph erlaubt keinen direkten Vergleich der beiden Werkstoffe wegen unterschiedlicher Abmessungen und Prüfbedingungen

sizes and conditions are compared (cf. Tables 5 and 6, plots in Fig. 8 do not allow direct comparison between the two materials).

A surprising result of the experiments is that in the tests made at natural climate the non-coated LVL-beams were not more prone to the DOL-effect than the coated ones, Fig. 9. A probable explanation to this is that in the natural climate tests the beams did not suffer true cyclic moisture conditions but rather constant or monotonously changing moisture (decreasing in the spring and increasing in the autumn); and the direct effect of moisture is predominant over the effect of its changes.

7
Conclusions

The most important conclusion to be made is that larger beam cross sections are less prone to reduction of time to failure due to moisture variations than are smaller cross sections. This is an important aspect to be considered when assigning values to design parameters that determine the calculatory design strength reduction assigned to the size-effect and DOL-effect in design codes.

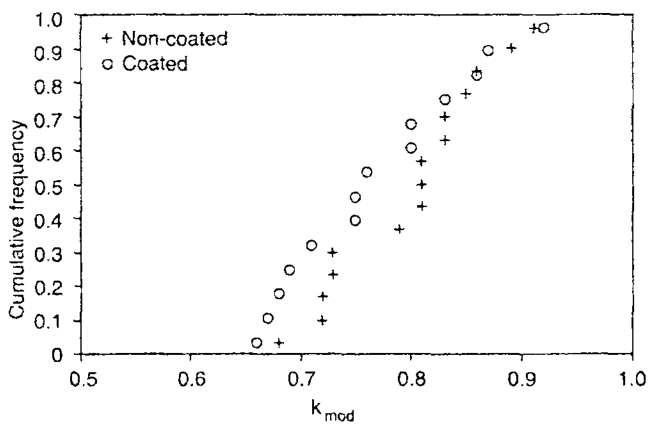

Fig. 9. Cumulative frequency plot of the strength factor k_{mod} for non-coated and coated LVL-beams at natural climate
Bild 9. Kumulative Häufigkeit des Festigkeitsfaktors k_{mod} für nicht beschichtete und beschichtete LVL-Träger bei in natürlichem Klima

The calculation methods for modelling of the DOL-effect developed during this project provide tools to further study the interaction effect of the cross-section size and moisture changes on the DOL-behaviour. The execution of full scale DOL-experiments with large cross-section sizes is very expensive. Therefore calculational methods that have been verified against an adequate number of DOL-tests in different environments are needed for assessing the DOL-behaviour in a wide range of conditions. The work has provided both – empirical data for the assessment of the magnitude of the DOL-effect in different conditions and produced models that can be put to use for such work.

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